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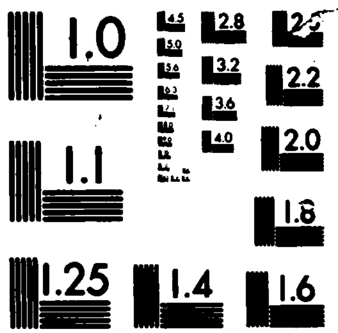

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Polytechnic Institute of New York

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November 1, 1985

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FINAL TECHNICAL REPORT

Millimeter Wave Generation by Relativistic Electron Beams

October 1, 1982-September 30, 1985

for

Air Force Office of Scientific Research
Arlington, Virginia

under

Grant No. AFOSR-83-0001

Submitted by

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The classical technique of transformation and chacteristics is employed to analyze the problem of strong turbulence in unmagnetized plasmas. The effect of resonance broadening and perturnation expansion are treated simultaneously without time secularities. The renormalization procedure in the sense of Dupree and Tetreault [1] is used in the transformed Vlasov equation to analyze the turbulence and to derive explicitly a diffusion equation. Analyses are extended to imhomogeneous plasma and the relationship between the transformation and ponderomotive force is obtained.

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Table of Contents

I. Introduction

AFOSR awarded a research grant (Grant No. AF-AFOSR-83-0001) bearing the title "Millimeter Wave Generation by Relativistic Electron Beams" to the Polytechnic Institute of New York with Professor S.P. Kuo as the Principal Investigator and Professor B.R. Cheo as the Co-Principal Investigator for one year beginning October 1, 1982. This grant has been renewed for two additional years. Under the support of this research grant, a number of investigations have been pursued, and many of them have yielded positive results which were published as journal papers. The investigation covered by the grant deals with the generation of millimeter waves by means of a relativistic electron beam and the collective phenomena associated with the interactions between the plasmas and the electromagnetic waves. During the past funding periods, the main scope of the research efforts has involved theoretical studies of physical phenomena observed in the laboratory experiments and computer simulations. At present, several theoretical topics have been successfully addressed, and the experimental program has also been started. In the area of experimental activities, significant progress has been made in the study of excitation of electrostatic ion cyclotron waves in a microwave sustained plasma and ordering of equipment for the cusptron device, a high harmonic microwave source. AFOSR has continuously supported our experimental and theoretical programs with a new grant awarded to the Polytechnic.

In Section II of this report, the publications of works supported by the present grant, which was duly acknowledged, is listed. Section III gives a brief description of the technical results of our research effort. The abstracts of the journal papers are included in Section IV as the Appendix supplement.

II. List of Publications

A. Journal Publications

1. S.P. Kuo and B.R. Cheo, "The Effect of the Bouncing Motion of Electrons on Electron Cyclotron Resonance Heating", Phys. Fluids, 26, 3018-3023, 1983.

2. S.P. Kuo and G. Schmidt, "Filamentation Instability in Magneto Plasmas", Phys. Fluids, 26, 2529-2536, 1983.

3. M.C. Lee and S.P. Kuo, "Excitation of Upper Hybrid Waves by a Thermal Parametric Instability", J. Plasma Physics, 30, 463-478, 1983.

4. S.P. Kuo and M.C. Lee, "Oscillating Two Stream Instability of Ducted Whistler Pump", Phys. Fluids, 27, 1434-1438, 1984.

5. S.P. Kuo and B.R. Cheo, "Analysis of Electron Cyclotron Maser Instability", Physics Letters A, 103A(9), 427-432, 1984.

6. S.P. Kuo and B.R. Cheo, "Relativistic Adiabatic Invariants of Electron and Motion under ECRH", Physics Letters A, 109A(1,2), 39-42, 1985.

7. M.C. Lee and S.P. Kuo, "Earth's Magnetic Field Perturbations as the Possible Environmental Impact of the Conceptualized Solar Power Satellite (SPS)", Journal of Geophysical Reserach, 89(A12), 11043-11047, 1984.

8. S.P. Kuo, M.C. Lee and Steven C. Kuo, "A Theoretical Model of Artificial Spread F Echoes", Radio Science, 20(3), 546-552, 1985.

9. M.C. Lee and S.P. Kuo, "Simultaneous Excitation of Large-Scale Geomagnetic Field Fluctuations and Plasma Density Irregularities by Powerful Radio Waves", Radio Science, accepted for publication, 20(3), 539-545, 1985.

10. S.P. Kuo, "Turbulance in Unmagnetized Vlasov Plasmas", Energy Conversion, accepted for publication, 25(3), 1985.

11. S.P. Kuo and G. Schmidt, "Interaction of Relativistic Electron Beam with Large Amplitude Electromagnetic Wave in a Uniform Magnetic Field", Journal of Applied Physics, 58, 3646, 1985.

B. Proceedings Issued Articles:

1. S.P. Kuo and M.C. Lee, "Modulational Instability of Lower Hybrid Waves", 1984 International Conference on Plasma Physics, June 1984, Switzerland, P17-4, p. 219.

2. M.C. Lee and S.P. Kuo, "Ionospheric and Magnetospheric Modifications Caused by the Injected ULF Waves", 1984 International Conference on Plasma Physics, June 1984, Switzerland, P11-11, p. 139.

3. M.C. Lee, J.A. Kong, H.C. Carlson, and S.P. Kuo, "Ionospheric Modifications by HF Heaters", AGARD Conf. Proc., 1985.

C. Conference Articles:

1. S.Kuo and B. Cheo, "Second Harmonic Cyclotron Radiation from a Relativistic Electron Beam", Bull. Amer. Phys. Soc., 27, 1074, 1982.

2. B.R. Cheo and S.P. Kuo, "The Effect of Mirror Bouncing of Electrons on ECRH", Bull. Amer. Phys. Soc., 27, 1079, 1982.

3. Y.F. Lan, S.P. Kuo and B.R. Cheo, "Saturation of Electron Cyclotron Maser Instability Driven by a Loss-cone Distribution", IEEE International Conference on Plasma Science, 83CH1847-3, 78, 1983.

4. S.P. Kuo, B.R. Cheo and Y.F. Lan, "Analysis of Electron Cyclotron Maser Instability", IEEE International Conference on Plasma Science, 83CH1847-3, 78-79, 1983.

5. S.P. Kuo and S. Chi, "Superadiabetic Invariants for Electron Cyclotron Heating of Relativistic Plasma", IEEE International Conference on Plasma Science", 83CH1847-3, 96, 1983.

6. B.R. Poole, B.R. Cheo, S.P. Kuo and M.C. Tang, "RF Generated Currents in a Magnetized Plasma Using a Slow Wave Structure", IEEE International Conference on Plasma Science, 83CH1847-3, 97, 1983.

7. B.R. Cheo, S.P. Kuo and E. Levi, "Nonlinear Evolution of Electron Cyclotron Maser Instability", Bull. Amer. Phys. Soc., 28(8), 1060, 1983.

8. S.P. Kuo, E. Levi and B.R. Cheo, "Saturation of Loss-Cone Electron-Cyclotron Maser Instability by Quasi-Linear Diffusion Process", Bull. Amer. Phys. Soc., 28(8), 1060, 1983.

9. S.P. Kuo and M.C. Lee, "Thermal Oscillation Two-Stream Instability of Whistler Pump", Bull. Amer. Phys. Soc., 28(8) 1106, 1983.

10. S. Chi and S.P. Kuo, "Superadiabaticities of Electron Trajectory under ECRH", Bull. Amer. Phys. Soc., 28(8), 1180, 1983.

11. M.C. Lee and S.P. Kuo, "On the Microwave-Ionosphere Interation", Bull. Amer. Phys. Soc., 29(8), 1192, 1984.

12. S.P. Kuo and M.C. Lee, "A Modulational Instability of Lower Hybrid Waves", Bull. Amer. Phys. Soc., 29(8), 1308, 1984.

13. S.P. Kuo and B.R. Cheo, "Analysis of the Electron Cyclotron Maser Instability", Bull. Amer. Phys. Soc., 29(8), 1378, 1984.

14. S.C. Kuo, S.P. Kuo and B.R. Cheo, "The Effect of Relativistic Detuning on ECRH", Bull. Amer. Phys. Soc., 29(8), 1430, 1984.

15. S.P. Kuo and E. Levi, "Thermal Instability Near the Electrodes of MHD Channels", IEEE International Conference on Plasma Science, 85CH2199-8, 63, 1985.

16. S.P. Kuo and M.C. Lee, "Spectral Broadening of Lower Hybrid Waves via Modulational Instability", IEEE International Conference on Plasma Science, 85CH2199-8, 84, 1985.

17. K.K. Tiong, S.P. Kuo and B.R. Cheo, "Observation of the Electrostatic Ion Cyclotron Wave in a Microwave Sustained Plasma", IEEE International Conference on Plasma Science, 85CH2199-8, 85, 1985.

18. S.P. Kuo and B.R. Cheo, "Analysis of the Gyrotron Traveling Wave Amplifier Operating at Cyclotron Harmonics", IEEE International Conference on Plasma Science", 85CH2199-8, 90, 1985.

III. Technical Results

Basically, the direction of investigations are divided into two general categories: A) Wave-plasma interactions near the cyclotron resonance for rf generation or for plasma heating, and B) Study of collective effects of plasmas on Electromagnetism. Both theoretical and experimental programs are covered in each category.

A. Wave-plasma Interactions near the cyclotron resonance for rf generation or for plasma heating:

1. Analysis of the Electron cyclotron maser instability

Conventional microwave devices such as the traveling wave tube or magnetron rely on a slow wave structure for their operation. Power density as well as voltage breakdown considerations place a lower limit on the dimensions of the structure. The electron cyclotron maser (gyrotron) mechanism, on the other hand, is through the fast wave coupling (waveguide) to convert the "transverse energy" of the relativistic electron beam into EM radiation. Moreover, Gyrotron operation does not rely on the fine structure of a waveguide or cavity, and it is thus that efficient generation of high power millimeter or submillimeter waves by the new device called Gyrotron is possible.

The Gyrotron is a device consisting of a hollow electron beam with sufficiently large transverse energy and a circular waveguide with an axial magnetic field provided by the external solenoids. Initially, the phases of the electrons in their cyclotron orbits are random. When electrons interact with EM wave of waveguide mode, azimuthal "phase bunching" can occur because of the relativistic mass change of the electrons. Those electrons that lose energy to the wave become lighter and accumulate phase lead while those electrons that gain energy from the wave become heavier and accumulate phase lag. The result of phase bunching is to induce a net current flow in or opposite to the direction of the wave field. If the wave frequency is slightly higher than the electron cyclotron frequency (or its harmonics), the direction of the induced current flow will be opposite to the direction of the wave field and the EM wave will be amplified coherently as an electron cyclotron maser instability.

In this work, the nonlinear evolution of electron cyclotron maser instability is studied analytically. Usually, there are two mechanisms which are responsible for the saturation of this instability. In our analysis, only the phase trapping of the gyrating particles in the wave is considered to be the only mechanism for saturation. This is reasonable if the initial beam energy is assumed to be large enough such that the effect of depletion of the rotational free energy of the electrons by the unstable wave becomes insignificant. Our approach to the problem starts with solving the equations of motion of a single electron moving in the wave fields and then follows with averaging the results over the initial random phase distribution to obtain the collective response of electrons to the wave fields. It is then found that the temporal evolution of the wave field amplitude can be governed by a single nonlinear equation which is derived self consistently as follows:

$$\frac{d^3}{dt^3} E_o + 2s \frac{d^2}{dt^2} E_o + (\Delta\omega_1^2 + c_o) \frac{dE_o}{dt} = a_o \Big(1 - \frac{\omega_o^2 - k_z^2 c^2}{\omega_o \Delta\omega_o} \frac{E_o^2}{32\pi n_o \gamma_o m_o c^2}\Big) \tag{1}$$

$$\int_o^t dt' E_o(t') \cos\langle\Delta\omega\rangle(t-t') - s\Big[2c_o E_o + \frac{a_o}{\Delta\omega_o} \int_o^t dt' E_o(t') \sin\langle\Delta\omega\rangle(t-t')\Big]$$

where

$$S = \frac{3}{8} \Big(\frac{e}{m_o c \gamma_o}\Big)^2 \frac{\omega_o c_o}{\Delta\omega_o \omega_p^2} (1 - k_z^2 c^2/\omega_o^2) E_o \int_o^t E_o(t') \cos\langle\Delta\omega\rangle(t-t') dt'$$

$$a_o = 2 \frac{\omega_p^2}{\gamma_o^2 \omega_o} \beta_\perp^2 (\omega_o^2 - k_z^2 c^2) W_N(\alpha) \Delta\omega_o$$

$$c_o = \frac{\omega_p^2}{\gamma_o \omega_o} (\omega_o - k_z v_{zo}) Q_N(\alpha)$$

$$\Delta\omega_1^2 = \Delta\omega_o^2 + \Big(\frac{e}{m_o c \gamma_o}\Big)^2 \frac{1}{2\beta_\perp^2} (1 - k_z v_{zo}/\omega_o)^2 \frac{Q_N^2}{W_N} E_o^2 + \frac{3}{4} \frac{\omega_o}{\gamma_o} \Big(\frac{e}{m_o c \gamma_o}\Big)^2$$

$$(1 - k_z v_{zo}/\omega_o)^2 Q_N E_o \int_o^t dt' E_o(t') \sin\langle\Delta\omega\rangle(t-t')$$

$\omega_p^2 = 4\pi n_o e^2/m_o$, n_o is the electron beam density averaged over the cross section of the guide, $\Delta\omega_o$ is the initial frequency mismatch, $W_N(\alpha) = J_N'^2(\alpha)$ and $\Omega_N(\alpha) = J_N'(\alpha)\frac{d}{d\alpha}[\alpha J_N'(\alpha)]$.

Equation (1) is integrated numerically in order to make quantitative comparison with the simulation results. Figures 1(a) and (b) present our numerical results of (1) for the temporal evolution of the field amplitude and the growth rate of the radiation, where the field amplitude and the time are normalized to $\varepsilon(\tau) = E_o(t)/(32\pi n_o \gamma_o m_o c^2)^{1/2}$ and $\tau = \Delta\omega_o t$ respectively. These results are in good agreement with those of the particle simulation . The preliminary results of this work has been published in the Physics Letters A Since the results deduced from this nonlinear equation are found to agree well with those of particle simulation, we are confident to use this equation to determine the power gain, conversion efficiency and also the dynamic properties of the collective response of electron beam to the excited wave fields. Under the grazing condition, one can also show that this equation is equally well for the study of the efficiency of the Gyrotron traveling wave amplifier operating at cyclotron harmonics.

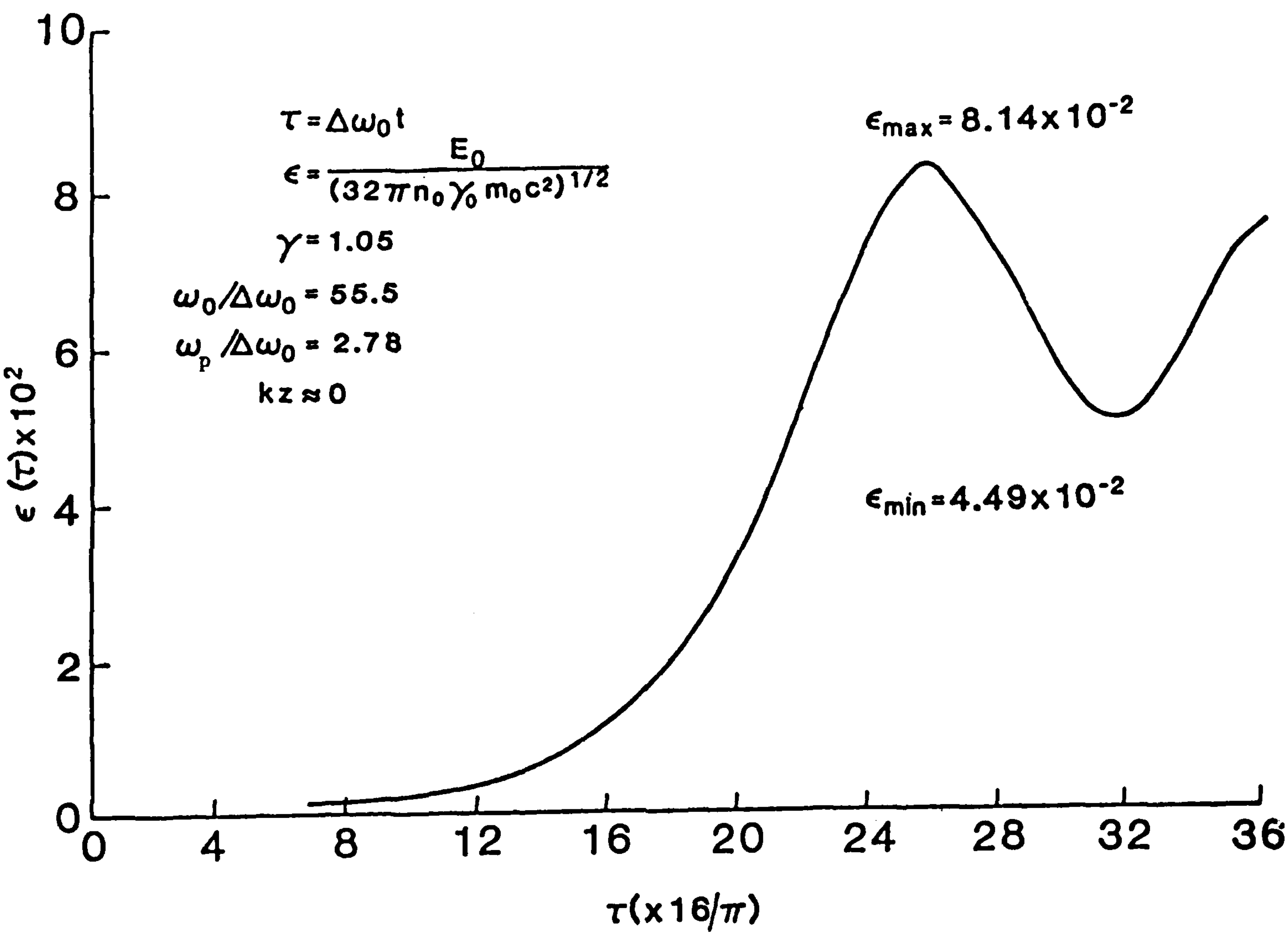

Fig. 1a - Radiation field amplitude evolving in time, $\epsilon_{max} = 8.14 \times 10^{-2}$ and $\epsilon_{min} = 4.49 \times 10^{-2}$ are in good agreement with the results of particle simulation.

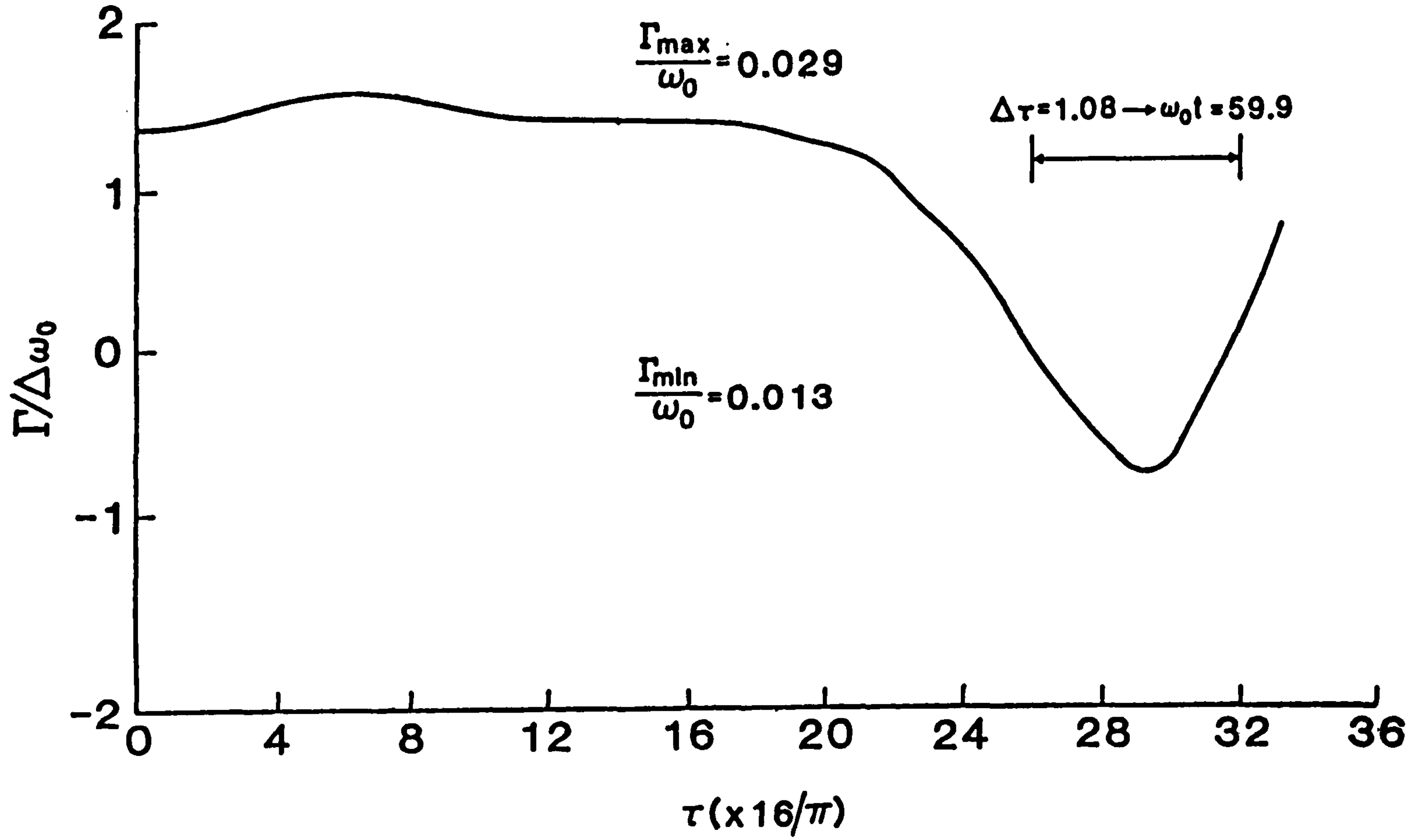

Fig. 1b - Growth rate vs time.

2. The Effect of the Bouncing Motion of Electrons on Electron Cyclotron Resonance Heating

The commonly recognized mechanism for achieving effective electron heating is the electron cyclotron resonance heating, which is also one of the damping mechanisms of the electron cyclotron Maser instability. It is important to note that the heating efficiency not only depends on the "initial" heating rate, but also on the "effective" heating time. This is why resonance heating is effective, because at resonance the phase difference between heating force and particle velocity becomes constant (fundamental resonance case) in the linear region and continuous energy flow from wave to charge particle (or vice versa) can be achieved. However, an exact resonance condition is not easy to be arranged in reality, and a small mismatch to the resonance condition means a strong deterioration in the "effective" heating time and so in heating efficiency.

In a uniform magnetic field case, for instance, if the heating wave is not exactly normal incidence (i.e. $k_{||} \neq 0$) and also if there is no other imposed force field in the system, the $k_{||}z$ phase angle in the wave fields can introduce a detuning effect of frequency mismatch to most of the charge particles and the continuous heating scheme breaks down. Unless other effects such as collisions, stochasticity and the bouncing effect considered in this work, etc., are set into the system to randomize the detuning phase, efficient heating cannot be achieved.

In this work, the important effect of the bouncing motion of electrons on ECRH has been illustrated by considering a case that electrons interact resonantly with the incident EM wave in a uniform background magnetic field and an imposed bouncing force field. The nonlinear evolution of the bounce amplitude has also been studied and the results of focusing and bunching of the excursion amplitude have been obtained in agreement with the experimental observation. The results of this analysis also show that the bouncing motion of electrons serves to alleviate the detuning effect of frequency mismatch and efficient heating can be achieved. Kinetic temperature is found to increase algebraically in t^2 for the fundamental resonance and to increase faster than an exponential in t for the second harmonic heating. This work has already been published in The Physics of Fluids.

3. Relativistic Adiabatic Invariants of Electron Motion Under ECRH:

Another approach to understanding how a small mismatch to the resonance condition can deteriorate the heating efficiency is through the adiabatic invariants of the motion of the charge particle in the heating wave fields. Since the heating waves are frequently of such magnitude to drive electrons to relativistic velocities, it would be of interest to derive these invariant relations for a relativistic plasma.

In this work, we consider the nonlinear interaction of a single elctron with an electromagnetic wave near a cyclotron harmonic, i.e., $\omega \sim N\Omega$, where ω is the frequency of the heating wave, $\Omega = e B_o/\gamma m_o c$ is the relativistic cyclotron frequency. $\gamma = (1+P^2/m_o^2c^2)^{1/2}$ is the relativistic factor and N is an integer. Electrons resonant trajectory is found to be governed by three invariants :

$$(\gamma v_z - k_z N\Omega_o/k_\perp^2)^2 - c^2(\gamma - N\Omega_o k^2/k_\perp^2\omega)^2 = \text{constant in time} = A_1 \qquad (2)$$

$$\gamma - (\omega/k^2c^2)(k_z\gamma v_z + \Omega_o \alpha^2/2N) = \text{constant in time} = A_2 \qquad (3)$$

$$J_N(\alpha)\sin\varphi_N - (k_\perp^2/k^2)[(\gamma v_z - \gamma_o v_{zo}) - (k_z c^2/2N\Omega_o)(\Omega_o/k_\perp c)^2(\alpha^2 - \alpha_o^2)]/v_q = \qquad (4)$$

$$= \text{constant in time} = A_3$$

where $\Omega_o = e B_o/mc$ is the nonrelativistic electron cyclotron frequency, k and ω are the wave vector and the frequency of the heating wave respectively, $\alpha = k_\perp v_\perp/\Omega$, ϕ_N is the phase angle, subscript o stands for the initial value, $v_q = eE/m\omega$ the quiver velocity of the heating field, and J_N is the Bessel function of order N.

We, therefore, have shown that the electron trajectory in the phase space of polar coordinates (α, φ_N) is governed by the invariant relation (4), which is coupled to the other two invariants (2) and (3). The second term on the LHS of (4) manifests the effect of detuning on resonance interaction, where the first term $(\gamma v_z - \gamma_o v_{zo})$ in the parenthesis is attributed to the relativistic effect and the second term in that arises from the oblique propagation of the heating wave (i.e. $k_z \neq 0$).

If we focus on relativistic detuning effect only and thus set $k_z = 0$, i.e., considering normal incidence case, the three invariants (2), (3) and (4) then reduce to

$$\gamma^2 v_z^2 - \gamma_o^2 v_{zo}^2 = c^2(\gamma-\gamma_o)(\gamma+\gamma_o - 2N\Omega_o/\omega) \quad (5)$$

$$\gamma-\gamma_o = (\omega\Omega_o/2Nk^2c^2)(\alpha^2 - \alpha_o^2) \quad (6)$$

and

$$J_N(\alpha)\sin\varphi_N - (\gamma v_z - \gamma_o v_{zo})/v_q = A_3 \quad (7)$$

respectively.

Without the second term on the LHS of (7), it reduces to the non-relativistic result $J_N(\alpha)\sin\varphi_N$ = constant in time which shows that the result of resonance interaction is to change α and φ_N continuously and simultaneously, following a closed contour in the polar α - φ_N coordinate space. However, the relativistic effect provides a coupling between $v_\perp$ and v_z, i.e., (5) and (6), from which the effect of detuning the resonance interaction arose from the change of the electron cyclotron frequency with the energy can be expressed in a form as the second term on the LHS of (7). The continuous heating process will then be interrupted by this detuning effect. This effect can be weaken, however, by increasing the intensity of the heating wave (i.e., v_q). From the ratio of (5) to (6), the result of the ratio of parallel energy gain to the perpendicular energy gain for each electron is obtained as

$$(\gamma^2 v_z^2 - \gamma_o^2 v_{zo}^2)/(\gamma^2 v_\perp^2 - \gamma_o^2 v_{\perp o}^2) = \frac{1}{2N}\left(\frac{\Delta\omega_o}{\Omega(o)} + \frac{\Delta\omega}{\Omega}\right) \approx (\Delta\omega_o + \Delta\omega)/2\omega$$

where $\Delta\omega = \omega - N\Omega_o/\gamma$ and $\Delta\omega_o = \Delta\omega(o)$. It shows that if $\Delta\omega_o + \Delta\omega < 0$, $\gamma v_\perp$ and γv_z change in a different way. Furthermore, if $\Delta\omega_o < 0$, i.e., initially there is a mismatch frequency between the wave and the gyrating electrons.

During the period that the electron gains energy from the wave the mismatch frequency is also reduced so that the interaction period of gaining energy from the wave is increased. On the other hand, during that period when electron loses energy to the wave the mismatch frequency is increasing and the period of losing energy to the wave is reduced. On the average, the electron will then gain energy from the wave in this case. Since the change of $\gamma^2 v_z^2$ is a small fraction of the change of $\gamma^2 v_\perp^2$, we thus conclude that the relativistic effect will give rise to the perpendicular heating and simultaneously cause the parallel cooling. While in the case $\Delta\omega_o + \Delta\omega > 0$ and $\Delta\omega_o > 0$, similar argument gives the conclusion that electron is losing energy to the wave on the average. Since γv_z and $\gamma v_\perp$ have to change in the same manner, i.e., increase or decrease together. Therefore, on the average the result of the interaction between wave and electrons in this case is also to reduce the parallel energy of the electrons.

Since in both cases $|\gamma v_z|$ is decreasing on the average, we hence conclude that the relativistic effect can also impose a focusing effect on the electron trajectory if the electron is, for example, bouncing back and forth about a "mid-plane." A more rigorous proof of this relativistic focusing effect incorporating the electron bounce motion in the analysis is under investigation. A manuscript summarizing the analytical results of this work has been published in the Physics Letters A

B. Study of Collective Effects of Plasmas on Electromagnetism

1. Filamentation (Modulation) Instability in Magneto Plasma

A large amplitude, initially uniform, wave propagating in a plasma can break up into filaments due to the filamentation instability. This occurs when small perturbations in the plasma density which result in a modulation of the plasma dielectric constant and wave distribution, which in turn increases the density perturbation. There are two known physical mechanisms by which a modulated wave changes the density distribution of the plasma.

The first mechanism is the ponderomotive force (radiation pressure). Particles are pushed away from regions of higher wave intensity by the ponderomotive force, giving rise to density ducts that act as light pipes in which the wave filaments propagate. This is the dominant process in collisionless or weakly collisional plasmas, like those encountered in laser-plasma interactions.

The second mechanism is thermal filamentation, which occurs in highly collisonal plasma. In this process electrons in regions of larger wave intensity are preferentially heated, and the thermal expansion of these electrons produces the density ducts that guide the waves. This is the dominant mechanism in many ionospheric applications.

In this work the effect of the magnetic field on the instability is included, as well as both the thermal and ponderomotive effects on particle motion. The price payed for this generality is a very complicated dispersion relation. We show that in various limiting cases the known results are recovered.

The dispersion relation is derived in the usual fashion. A high frequency pump field couples nonlinearly to two high frequency side bands and a purely growing, nonresonant, filamentation mode. All modes are affected by the magnetic field. Both the plasma and the pump are initially uniform in space aside of the small perturbation. The dispersion relation can then be analyzed for thresholds as well as growth rates, for various cases like ordinary and extraordinary pump fields, and for filamentation directions with respect to the background magnetic field. It is shown that the filamentation of O mode pumps propagating at an arbitrary angle with respect to the magnetic field has to be magnetic field-aligned, but not for X mode pumps. This work has been published in The Physics of Fluids.

2. Excitation of Upper-Hybrid Waves by a Thermal Parametric Instability

A purely growing instability characterized by a four-wave interaction has been analyzed in a uniform, magnetized plasma. Up-shifted and down-shifted upper hybrid waves and a non-oscillatory mode can be excited parametrically by a pump wave of ordinary rather than extraordinary polarization in the case of ionospheric heating. The differential ohmic heating force dominates over the ponderomotive force as the nonlinear effect on the excitation of purely growing modes. The beating current at zero frequency produces a significant stabilizing effect on the excitation of short scale modes by counterbalancing the destabilizing effect of the differential ohmic beating. The nonlinearities for the upper hybrid sidebands come from the beating currents driven by the pump field on the density perturbation of the purely growing modes. The threshold and the growth rates as well as the instability zone are determined. The effect of ionospheric inhomogeneity is estimated, which tends to raise the thresholds of the instability. When applied to ionospheric heating experiments, the present theory can explain the experimental observations such as the excitation of magnetic field-aligned plasma lines and ionospheric irregularities with a continuous spectrum ranging from metre-scale to hundreds of metre-scale. Further, the proposed mechanism may become a competitive process to the parametric decay instability excited at higher altitude and be responsible for the overshoot phenomena of the plasma-line enhancement observed in Arecibo heating experiments. This work has been published in the Journal of Plasma Physics.

3. Oscillating Two-Stream Instability of a Ducted Whistler Pump

The interest in the RF heating of plasmas has stimulated extensive studies on the parametric instabilities driven by whistler pumps in either ducted or nonducted mode. In this work, we investigate the parametric excitation of a magnetic field-aligned zero frequency mode together with two lower hybrid sidebands by a ducted whistler pump. The influence of various nonlinear effects on this instability is evaluated. The thermal focusing force that results from the differential ohmic heating of the whistler pump and the lower hybrd sidebands dominates in exciting this instability in the large-scale regime. However, the non-oscillatory beating current that is driven bv the whistler pump field on the density fluctuations of lower hybrid sidebands becomes overriding to the thermal focusing force effect in the short-scale regime of the instability.

In any case, the ponderomotive force (i.e., the radiation pressure force) does not have significant effect on this instability as long as the phase velocity of the whistler pump is much larger than the electron thermal velocity. The applications of this theory to space and laboratory plasmas are studied. It is found that the large scale instability can be excited in ionospheric plasmas in the wave injection experiments performed at Siple and may be responsible for the enhanced airglow observed during the experiments. It is also found that this process may be able to explain the correlation between the excitation of lower hybrid waves and the lightning storms. In contrast, only the short scale instability can be excited in the plasma fusion devices. This work has been published in The Physics of Fluids.

(4) Earth's Magnetic Field Perturbation as One Possible Environmental Impact of the Conceptualized Solar Power Satellite

The results of this study conclude that the earth's magnetic field can be significantly perturbed locally by the microwave beam transmitted from the conceptualized solar power satellite (SPS) at a frequency of 2.45 GHz with incident power density of 230 W/m^2 at the center of the beam. The simultaneous excitation of the earth's magnetic field fluctuations and ionospheric density irregularities is caused by the thermal filamentation instability of microwaves with scale lengths greater than a few hundred meters. Earth's magnetic field perturbations with magnitudes ($\simeq$ a few tens of gammas) comparable to those in magnetospheric substorms can be expected. Particle precipitation and airglow enchancement are the possible, concomitant ionospheric effects associated with the microwave-induced geomagnetic field fluctuations. Our present work adds earth's magnetic field perturbations as an additional effect to those such as ionospheric density irregularities, plasma heating, etc., that should be assessed as possible environmental impacts of the conceptualized solar power satellite program. This work has been published in The Journal of Geophysical Research.

(5) A Theoretical Model of Artificial Spread-F Echoes

Our previous work [Kuo and Schmidt, Phys. Fluids, 26, 2529, 1983] on filamentation instability of EM waves in magnetic-plasmas has shown that the irregularities excited by the O-mode pump and by the X-mode pump have different polarization directions. The irregularities excited by the O-mode pump are field aligned and are polarized in the direction perpendicular to the meridian plane. By contrast, the irregularities excited by the X-mode pump are polarized in the meridan plane and are, in general, not field-aligned. These results are realized to agree with the observations on spread-F phenomena during the ionospheric heating experiments, namely, the excitation of differently polarized irregularities by differently polarized heater is responsible for the different occurrence frequencies of artificial spread-F noticed at Arecibo, Boulder, and Tromsø. To enhance our contribution to the spread-F problem, we further developed a theoretical model for artificial spread-F echoes. In this work, the relationship between the spread-F echoes and the HF wave-induced irregularities is studied by the proposed model. The effect of the irregularity polarizations, scale length, and the geomagnetic dip angle on the spread-F echoes have been examined. This work has been published in Radio Science

(6) Simultaneous Excitation of Earth's Magnetic Field Fluctuations and Plasma Density Irregularities by Powerful Radio Waves from VLF to SHF Bands

The physical mechanism of thermal filamentation instability of radio waves whose frequencies can be as low as in the VLF band and as high as in the SHF band is elaborated in this study. We have shown that this instability can excite large-scale magnetic and plasma density fluctuations simultaneously in the ionosphere and magnetosphere. Significant geomagnetic field fluctuations can be excited in all of the cases investigated. The motivation for this work stems from the need for detailed information on the effects of electron density fluctuations and geomagnetic fluctuations on communications, navigation, and radar systems. This work has been published in Radio Science.

(7) Turbulence of Unmagnetized Vlasov Plasmas:

During the past two decades turbulence theories of Vlasov plasmas have been studied extensively. Important advances in this field have been made by many investigators, such as: Mikhailovskii , Kadomtsev , Dupress , Orszag and Kraichnan , Weinstock , Dum , Marcuvitz , Kuo and Cheo , and Choi and Horton ,etc. The original formulation of weak-turbulence theory was obtained by an iterative solution of the Vlasov equation. In this approach, one has to face two fundamental difficulties as pointed out by Dupree: (a) non-analyticity in the perturbation parameter ε (which is usually proportional to the field strength), and (b) time-secularities in the individual terms of the perturbation solution . The first attempt to improve weak-turbulence theory were proposed by Dupree . He advanced a singular perturbation theory which is based on the use of a statistical set of perturbed trajectories for the test waves instead of the unperturbed trajectories conventionally used in the solution of the Vlasov equation. His results have demonstrated that the resonance interactions between particles and waves are broadened by the turbulent electric fields, and certain time secularities are hence avoided. However, in this approach only the first diffusion term was derived and results of weak-turbulence theories in the appropriate limit were not recovered. Later Weinstock developed a statistical theory of strong plasma turbulence along a similar line of arguments. Cumulant expansions were introduced to evaluate average "Vlasov propagators", and to rigorously treat the velocity dependence of the diffusion coefficient. With this procedure, certain approximations and heuristic arguments found in Dupree's important articles became unnecessary. Again, because of the complexity of the average propagators, only first diffusion term was considered.

Therefore, one of the central problems in the strong-turbulence theory is that of how to obtain a renormalization procedure such that the perturbation expansion and Dupree's idea of resonance broadening can be treated simultaneously. The time-secularity in the individual terms of the perturbation expansion may then be removed. The results of weak-turbulence theories should then be recoverable in the appropriate limits. This approach was first successfully brought out by Dupree and Tetreault in studying the collisionless drift wave turbulence. Based on previous renormalized theories, they showed that the simplest versions of the theory can be obtained by using the linear formula except that the unperturbed orbits used in the linear theory be replaced with certain averages of test particle orbits in the turbulent plasma. Resonance broadening and enhanced damping due to the incoherent scattering of the particle orbits by waves are then assumed to be the intrinsic characteristics of the turbulent plasma. This enabled them to further the theory to include the higher nonlinear terms and eliminate certain problems contained in the previous theory Their success in treating the strong $\vec{E}\times\vec{B}$ drift turbulence lies with the fact that the dominant broadening effect comes from the form of the enhanced damping: $\exp[-(k_\perp^2 D_\perp t)]$, where $D_\perp$ is the spatial cross field diffusion coefficient. In this form, it is possible to apply the Fourier analysis used, and hence to obtain the renormalized diffusion equation containing the higher order nonlinear terms. In the case of unmagnetized plasmas, the resonant broadening effect takes the form $\exp[-(\frac{1}{3} k^2 D_u t^3)]$ where D_u is the velocity diffusion coefficient. The Fourier analysis approach used by Dupree and Tetreault is no longer applicable, because of the cubic power t dependence. A different method must be used.

In the practical applications, the strong-turbulence theory does have the advantage of giving a simple final result. Bezzerides and Weinstock have shown the saturation of parametric instabilities due to resonance broadening; and Dupree ,Weinstock and Williams ,Dum and Sudan ,and Dum and Dupree etc. have proposed the nonlinear damping of enhanced spatial diffusion coefficient as the stabilization mechanism of various instabilities in the magnetized plasmas. Another application of current interest is the turbulent heating of plasmas by strong electromagnetic waves. Heating rates can be calculated from the velocity diffusion coefficient which is derived from the renormalized turbulence theory. As shown in our previous theory of turbulent heating , when the diffusion coefficient obtained by incorporating the coherent pump field effect in the analysis of turbulent heating. Not only the heating of suprathermal tail was predicted, but also bulk heating of plasmas was predicted as consistent with the observations in the laboratory experiments and computer simulations

In this paper we consider the problem of strong turbulence in an unmagnetized Vlasov plasma. We employ the technique of characteristics and apply a transformation to the Vlasov equation. Our resulting equation has shown to offer advantages both conceptually and in practical applications. This is elaborated by using it to derive the nonlinear dielectric function which includes the effect of resonance broadening to all higher order terms. The basic features of weak turbulence are retained. A diffusion equation, which also includes the resonance broadening effect and retains the features of weak turbulence theory, is derived. We have also presented an extension of the theory to inhomogeneous background and shown the relationship between the transformation and the pondermotive force. This work has been accepted for publication in Energy Conversion.

8. Interaction of Relativistic Electron Beam with Large Amplitude EM Wave in a Uniform Magnetic Field:

We study the resonance interaction between an electron beam and a large amplitude electromagnetic wave having right hand circular polarization. They propagate co-linearly along a dc magnetic field $\vec{B}_o = B_o \hat{z}$. Full nonlinearity of the relativistic effect will be included in the analysis. We first analyze the responses of electrons to the wave fields from a single particle approach. The motion of a single electron is a dc magnetic field $\hat{z} B_o$ and the EM wave fields are governed by a set of coupled trajectory equations:

$$\frac{d}{dt} \vec{r} = \vec{v} \tag{8}$$

$$\frac{d}{dt} \vec{P} = -e[\vec{E} + \frac{1}{c} \vec{v} \times (\vec{B} + \hat{z} B_o)] \tag{9}$$

and

$$mc^2 \frac{d}{dt} \gamma = -e \vec{E} \cdot \vec{v} \tag{10}$$

where $\vec{E}=E_o(t)[\hat{x}\cos(kz-\omega t)-\hat{y}\sin(kz-\omega t)]$, $\vec{B}=\hat{z}\times\vec{E}$, $\omega = kc$ is assumed since $\omega \gg \omega_p$ for a tenuous beam; $\gamma = (1+P^2/m^2c^2)^{1/2}$ is the relativistic factor and m is the rest mass of the electron.

The z-component of (9) gives

$$\frac{d}{dt} P_z = - \frac{e}{c} \vec{E} \cdot \vec{v} \qquad (11)$$

This equation together with Eq. (10) determines an invariant of the motion as

$$\gamma(\omega-kv_z) = \text{const.} = c_o \qquad (12)$$

where $c_o = \gamma_o(\omega-kv_{zo})$.

From (12) and the definition of $\gamma = (1-v^2/c^2)^{-1/2}$, we find the relationship between $v_\perp$ and v_z as

$$v_z/c = [\alpha \pm \sqrt{1-(1+\alpha)(v_\perp^2/c^2)}]/(1+\alpha) \qquad (13)$$

where $\alpha = 1/\gamma_o^2(1-v_{zo}/c)^2$ is defined. Since v_z/c has to be real, one constraint can be deduced form (13), namely,

$$v_\perp^2/c^2 \le 1/(1+\alpha) \qquad (14)$$

which set the upper bound on the transverse velocity of the electron achievable through the interaction with the EM wave.

It implies that the acceleration of electron's transverse velocity by the EM wave fields is bounded. This is because the wave magnetic field gives rise to a Lorentz force whose transverse component acts to reduce the effective transverse electric force on electrons.

We now analyze the motion of electrons. Let $v^- = v_x - iv_y$ and $E^- = E_x - iE_y = E_o e^{i(kz-\omega t)}$, the two transverse components of (9) can be combined to be

$$m \frac{d}{dt} \gamma v^- + i\Omega m\gamma v^- = -eE^-(1-v_z/c) = -(ec_o/\omega)(E^-/\gamma) \qquad (15)$$

where $\Omega=\Omega_o/\gamma$, $\Omega_o = eB_o/mc$ and (12) is used to obtain the RHS of (15).

Equation (15) can be integrated formally to be

$$\gamma v^- = \gamma_o v_{\perp o}\, e^{-i(\theta_o + \int_o^t \Omega(s)ds)} - \frac{e c_o \omega}{m k^2 c^2}\, e^{-i\int_o^t \Omega(s)ds} \left\{ \int_o^t dt'\, e^{ikz_o}\, e^{i(\Omega_o - c_o)[\int_o^{t'} ds'/\gamma(s')]} \right. \tag{16}$$

$$\left. \times [E_o(t')/\gamma(t')] \right\}$$

where $\theta_o = \tan^{-1} v_{yo}/v_{xo}$, the invariant relation (12) and the z trajectory $z = z_o + \int_o^t v_z(s)ds$ have been used to simplify the expression of (16).

We now consider a special case $c_o = \Omega_o$, the electron beam is set resonant with the wave, the invariant relation (12) implies that the resonance condition $\omega = \Omega_o/\gamma + kv_z$ is maintained for the entire interaction period. Equation (16) thus reduces to

$$\begin{aligned} \gamma v^- &= \gamma_o v_{\perp o} e^{-i(\theta_o + \int_o^t \Omega(s)ds)} \\ &\quad - (e\Omega_o/m\omega) e^{i[kz_o - \int_o^t \Omega(s)ds]} \int_o^t dt'[E_o(t')/\gamma(t')] \end{aligned} \tag{17}$$

Substituting (17) into (11), yields

$$mc^2 \frac{d}{dt}\gamma = -e(E_o/\gamma)\{\gamma_o v_{\perp o}\cos(\theta_o + kz_o) - (e\Omega_o/m\omega) \int_o^t dt'[E_o(t')/\gamma(t')]\} \tag{18}$$

Defining a function $f(t) = \int_o^t dt'\, E_o(t')/\gamma(t')$, thus

$$f'(t) = E_o/\gamma \tag{19}$$

and (18) becomes

$$mc^2 \frac{d}{dt}\gamma = -e\{\gamma_o v_{\perp o}\cos(\theta_o + kz_o)\frac{d}{dt} f - (e\Omega_o/2m\omega)\frac{d}{dt} f^2\} \tag{20}$$

It is integrated to obtain the relation

$$\gamma = \gamma_o - (e/mc^2)[\gamma_o v_{\perp o}\cos(\theta_o + kz_o) f - (e\Omega_o/2m\omega) f^2] \tag{21}$$

Substituting (21) into (19), the resultant equation is integrated to find

$$\gamma_o f - \left(\frac{e}{2mc^2}\right)[\gamma_o v_{\perp o}\cos(\theta_o+kz_o)f^2 - (e\Omega_o/3m\omega)f^3] = F(t) \tag{22}$$

where $F(t) = \int_o^t dt' E_o(t')$.

From (21) and (22), the relationships between γ, f and F can be determined. Suppose that $\dot{E}_o$=const. and $v_{\perp o}=0$, e.g., considering only a single electron so that a self-consistent consideration of wave fields is not necessary, (21) together with (19) can show that γ is an increasing function of time. It then means that electron can gain energy indefinitely through the resonant interaction with the imposed EM wave fields. Since the transverse component of the electron velocity is bounded, it implies that electron can be accélerated indefinitely in the magnetic field direction. This is realized by the fact that there is no other force to counterbalance the acceleration force given by the parallel component of the Lorentz force of the wave magnetic field in that direction. Consequently, we can then conclude that only the negative sign in (13) holds initially. It is, however, that it turns to the positive sign once the maximum transverse speed $(v_\perp/c)_{max}=(1+\alpha)^{-1/2}$ has been reached. Thenceforth, $v_\perp$ decreases, but v_z increases continuously. The decrease of $v_\perp$ is caused by the increase of the electron relativistic mass and by the reduction of the effective transverse electric force on the electron as mentioned before.

We next determine the responses of the wave fields to the electron dynamics. This will be done by solving the wave equation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c^2}\frac{\partial}{\partial t}\vec{J} \tag{23}$$

Assuming that $\left|\frac{\partial}{\partial t}E\right| \ll |\omega E|$, and with the aid of (17), (23) can be reduced to

$$\frac{d}{dt}E_o = (2\pi n_o e/\gamma)[\gamma_o v_{\perp o}\cos(kz_o+\theta_o) - (e\Omega_o/m\omega)f] \tag{24}$$

where n_o is the density of the beam and an initial value problem is studied. Boundary value problem can also be analyzed in a similar way by replacing $\frac{\partial}{\partial t}$ by $v_z\frac{\partial}{\partial z}$, but further approximation $v_z \approx v_{zo}$ will be needed.

Since $E_o = F' = \gamma f'$, (24) can be written as

$$F'' + (\omega_p^2/2\gamma)[(\Omega_o/\omega)f - (m\gamma_o v_{\perp o}/e)\cos(k_{zo}+\theta_o)] = 0 \tag{25}$$

where $\omega_p^2 = 4\pi n_o e^2/m$. But $f/\gamma = \psi(F)$ a function of F, if $v_{\perp o} = 0$, so (25) is an equation for an anharmonic oscillator in F(t). Multiplying both sides of (25) by $F' = \gamma f'$, and integrating, one obtains

$$\frac{1}{2} F'^2 + (\omega_p^2/2)[(\Omega_o/\omega)(f^2/2) - (m\gamma_o v_{\perp o}/e)\cos(k_{zo}+\theta_o)f] = \frac{1}{2} E_o^2(0) \qquad (26)$$

Since $f = f(F)$, in the F coordinate (26) is the energy equation for wave trapped in a potential well, where the first term of the LHS of (26) represents the kinetic energy of the wave and the second term represents the potential energy of the wave stored in the beam. Consider first $v_{\perp o} = 0$ case. Since f=0 at F=0, thus the potential function is a symmetric potential well as shown in Fig. 2a. At the turning points of the potential well, F'=0, i.e. E_o=0, and both f and $|F|$ reaches the maximum. This simply means that the electrons have absorbed all the wave energy. Subsequently, the electrons start to give energy back to the wave so that wave amplitude is oscillating between zero and the initial value. In other words, the result of the resonant interaction between the electron beam and the wave is to cause the periodic intensity modulation of the wave. In this case, wave cannot be amplified. This is because in the beam frame wave can only lose energy. It is also realized all its energy to the electrons. It means that if the initial wave energy is high and the beam density is low, it will then take much longer to accumulate enough number of electrons in the path so that all the wave energy can be absorbed. Under this circumstance, the potential function becomes very flat as expected.

We next consider $v_{\perp o} \neq 0$ case. The potential function shown in Fig. 2b is a shifted symmetric well. The minimum of the potential function is now less than zero. Therefore, wave can be amplified in the regions of negative potential energy. This is because in the beam frame electrons still have transverse velocity. However, the result of the continuous interaction is again to cause periodic intensity modulation of the wave same as the previous case except the wave intensity is now oscillating between zero and a maximum larger than the initial value. This work has been published in the Journal of Applied Physics.

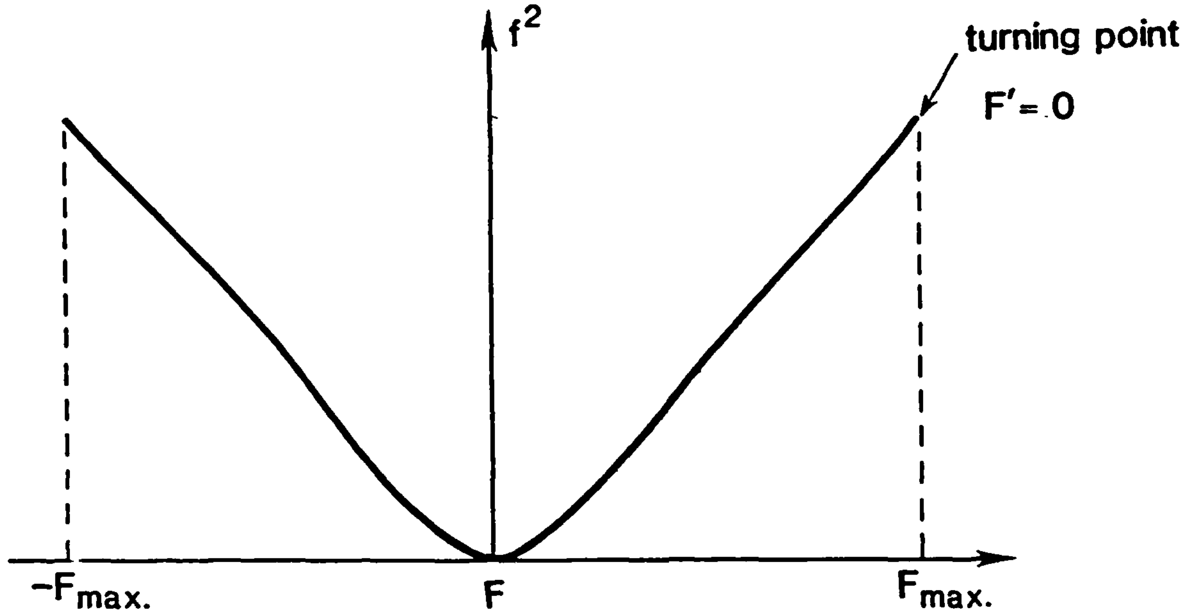

Figure 2a- Symmetric potential well seen by wave interacting resonantly with the electron beam.

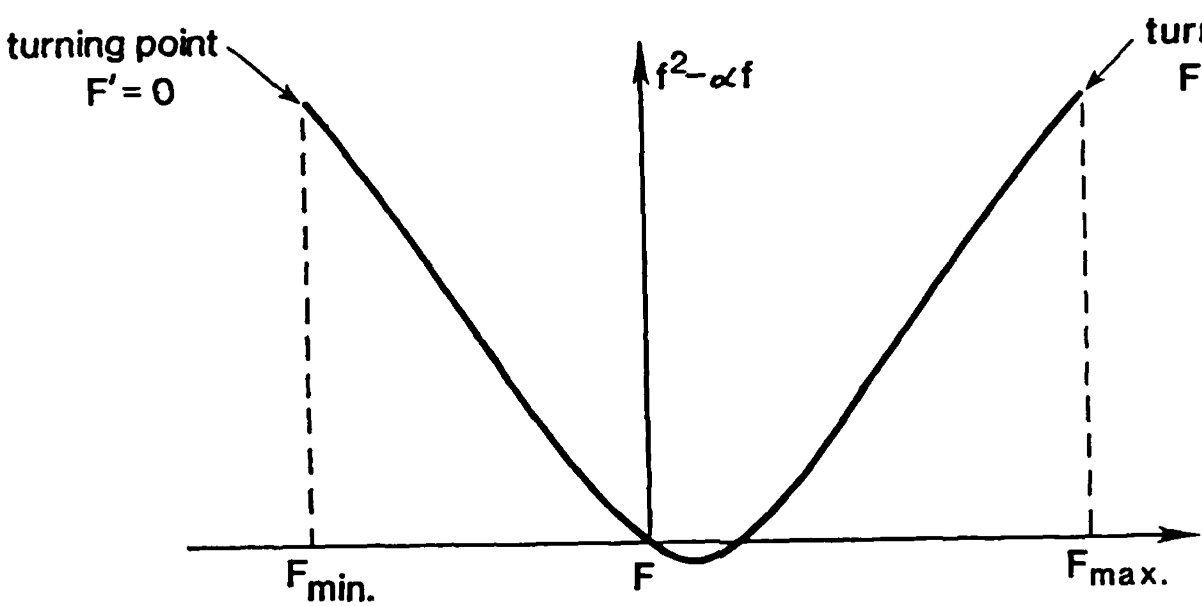

Figure 2b- Potential well for $v_{\perp o} \neq 0$ case, where $\alpha = 2\gamma_o(\omega v_{\perp o}/\Omega_o c)$ and $\cos(\theta_o + k_{zo}) = 1$ is used.

C. Experimental Progress

(1) Excitation of Electrostatic Ion Cyclotron Waves in a Microwave Sustained Plasma

The experimental set up consists of a Hollow Cathode Discharge (HCD) system, 15 cm in diameter and a vacuum chamber 2m in length as shown in Fig. 3. This linear device is divided into a source region which is separated from the drift region by a baffle anode. The magnetic field is provided by a set of 15 water cooled PEM coils (4 in source region and 11 in drift regions) each with resistance of 0.03 Ω. The magnetic field strength is of the order of 2.5 KG. The confining drift region magnetic field is spatially uniform to ~1% over an axial length of 1m.

In our present experiment, we use a frequency stabilized Klystron unit operating in the X band region as the source. A simplified block diagram of the experimental apparatus is shown in Fig. 4. The X-band is operating at the frequency of 9.23 GHz. The onset of the plasma is the discharge of a high frequency testla coil through one of the movable Langmuir probes [see Fig. 3]. With appropriate adjustment of the plasma parameters such as background gas pressure, drift region magnetic field and input microwave power, a highly quiescent and well confined plasma beam is sustained in the drift region. The background magnetic field and gas pressure are in the range of 1.5 KG to 2KG and 1 μ to 1.5 μ mercury pressure, respectively. The injected microwave (150w-300w) is transmitted through waveguide into the chamber by means of a horn mounted on the anode and plate. Since the EM wave in the waveguide is TE_{10} mode, the electric field in the chamber is linearly polarized in the direction perpendicular to the background magnetic field and almost uniformly distributed over the cross section of the chamber near the horn. The diagnostic devices employed in this experiment include axially and radially movable Langmuir probes so that the transverse and axial profile of the plasma and the excited instability may be investigated. A low frequency instability in the frequency range of 25 KHz to 100 KHz is excited parametrically through this microwave-plasma interaction. Its higher harmonics (the second and third harmonics) are also excited. Identification of the excited instability as the electrostatic ion clyclotron wave can be examined through the linear dependence between the frequency shift and the electron temperature change. The electron temperature variation is by the change of the input microwave power.

For the study of the temporal evaluation of the instability, a fast PIN diode switch having 20 ns rise and fall times will be used to modulate the microwave source which is fed into a Kylstron amplifier [see Fig. 4]. Between the PIN diode and the source, two variable attenuators are used to adjust the output levels of the microwave. This work is being continued. The preliminary results have been presented at the 1985 IEEE International Conference on Plasma Science.

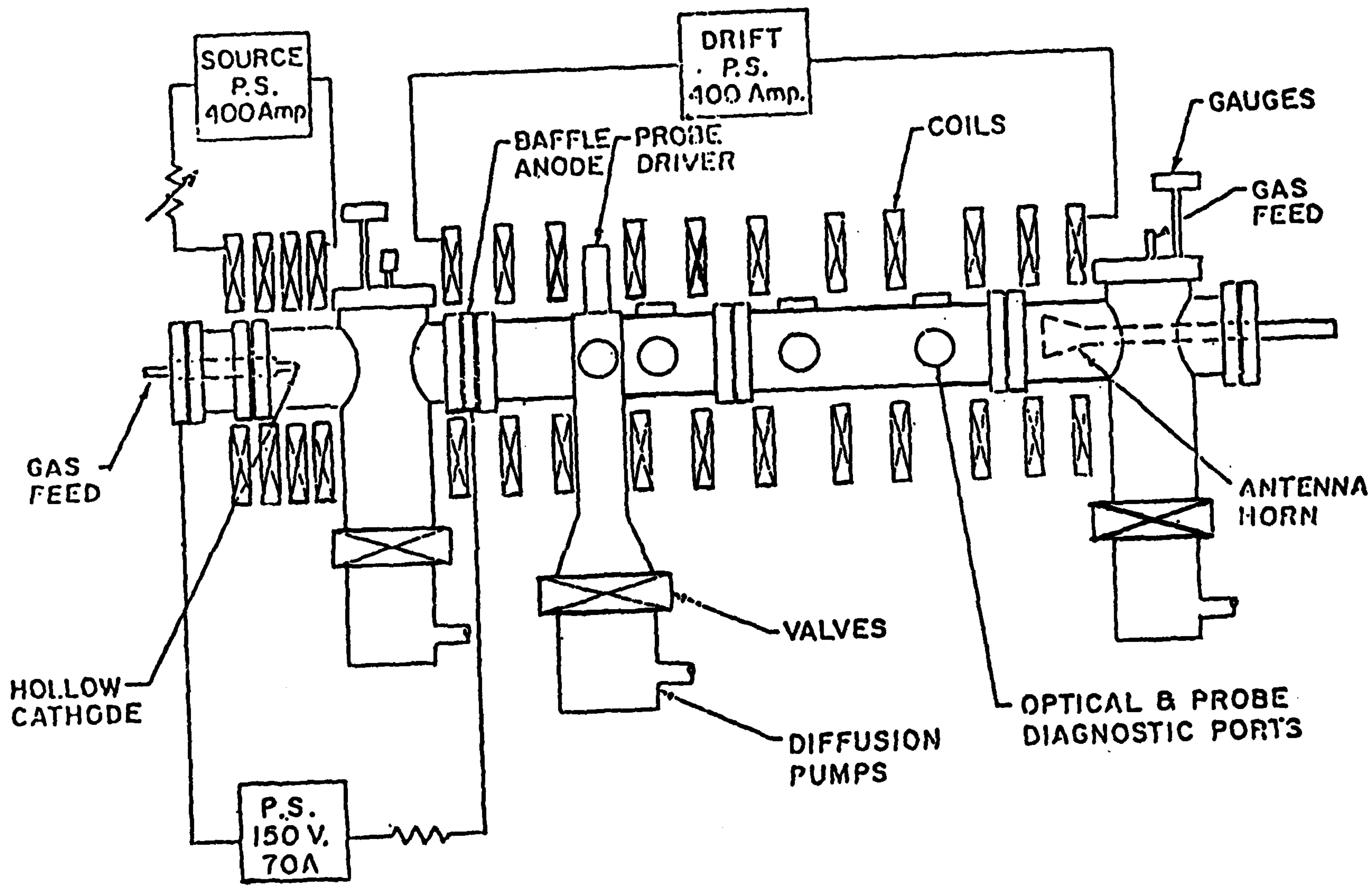

FIG. 3: HOLLOW CATHODE DISCHARGE PLASMA DEVICE

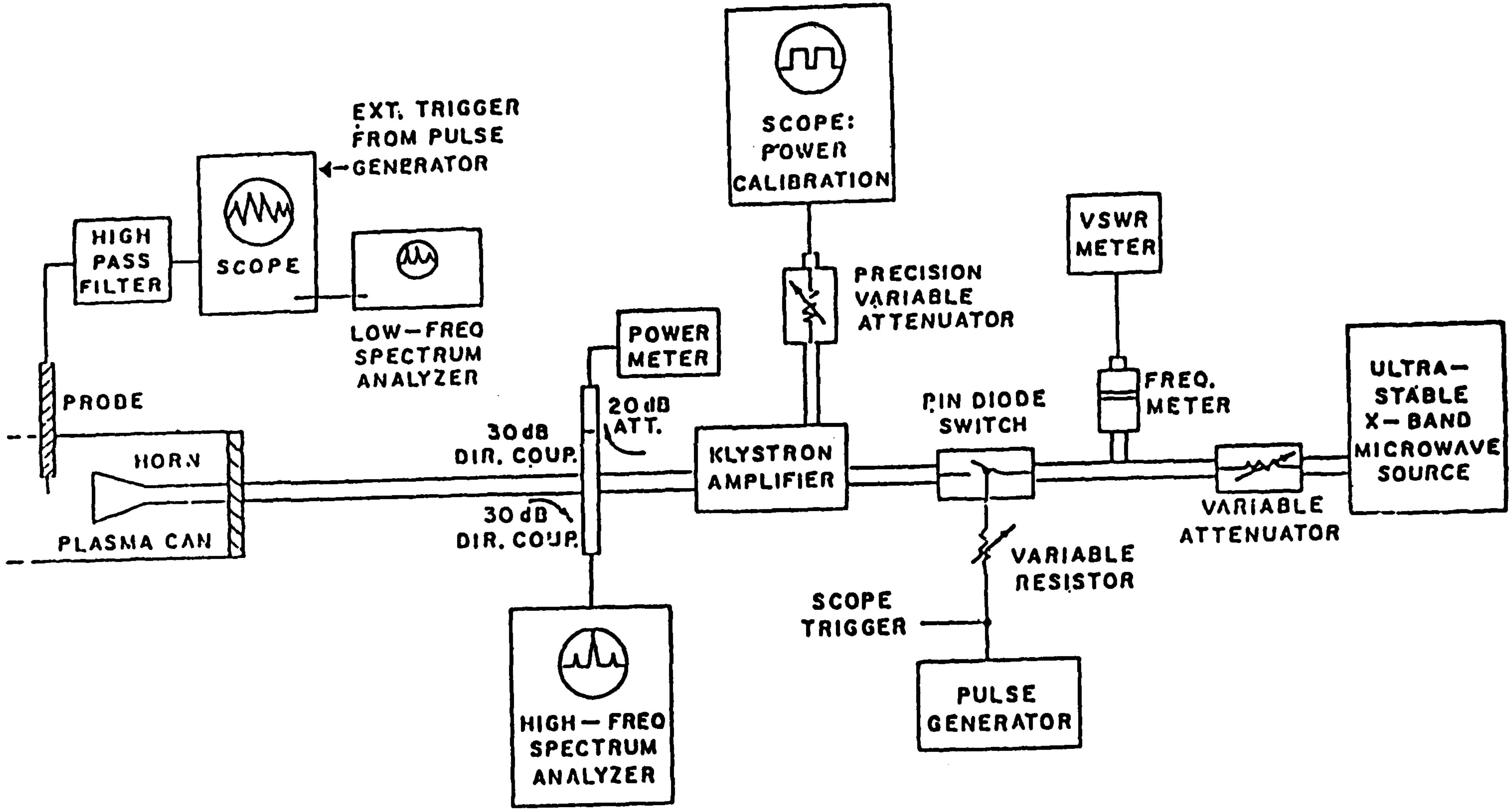

FIG. 4: MICROWAVE SYSTEM AND EXPERIMENTAL SET-UP

(2) <u>High Harmonic Electron Cyclotron Maser Device (Cusptron)</u>

We are now preparing to set up the cusptron device which will be similar to the one operated at Naval Surface Weapon Center (NSWC) and is shown in Figure 5 . Necessary equipment and parts are ordered and many of them have already been received. These include the ten magnetic coils, molecular sorption pumps and 4-1/2 digital multimeter for the monitor of the field current. Existing facilities include ion pump, 32 Mw pulse modulator, and three power supplies for the cusp field. The multivane magnetron type structure is being made in our Laboratory. Purchase orders for the other principal parts such as the electron gun, stainless steel chambers, and accessory diagnostic equipment have been processed.

In the cusptron device, the low energy rotating E-layer is produced by the magnetic cusp field set up by the diode coils and downstream coils. A soft iron plate which acts as the anode, is placed between the coils to narrow the cusp transition. Our multivane structures have N=6 and N=12 slots respectively. The predominant mode of radiation is either the sixth harmonics or the twelfth harmonics. Since magnetic field strength is in inverse proportion to the number of harmonics, the cusptron device, when in operation, offers compactness with reasonable efficiency.

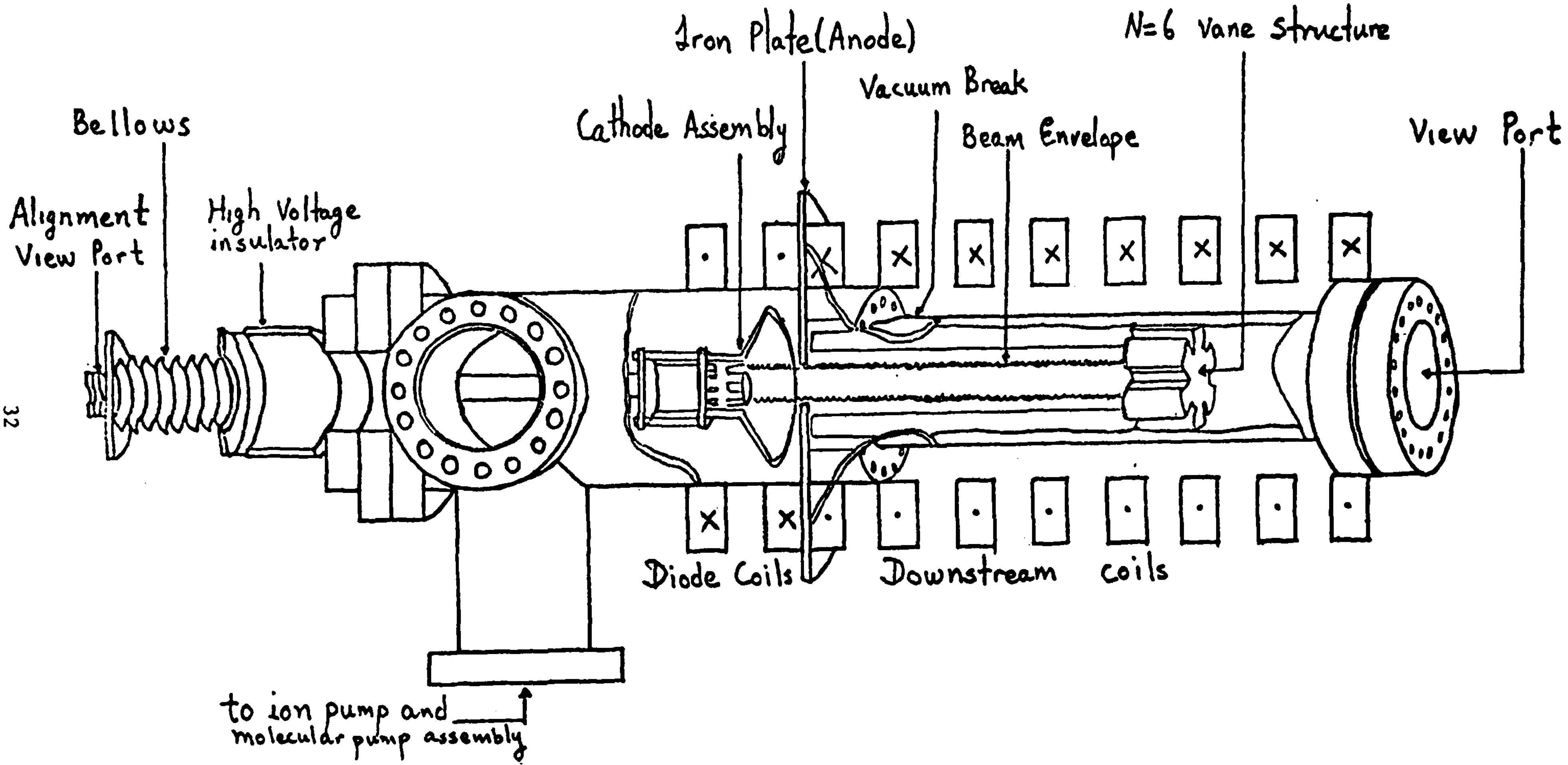

Fig 5 : Higher Harmonic Cusptron Device

THE EFFECT OF THE BOUNCING MOTION OF ELECTRONS ON ELECTRON CYCLOTRON RESONANCE HEATING

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ABSTRACT

Cyclotron resonance heating of bouncing electrons by an obliquely incident wave field is analyzed. Continuous interaction between electrons and wave fields throughout the entire range of electron excursion has been considered in the analysis. The results show that the bouncing motion of electrons serves to alleviate the detuning effect of frequency mismatch and efficient heating can be achieved. Kinetic temperature is found to increase algebraically in t^2 for the fundamental resonance and exponentially in t for the second harmonic heating. Due to the interaction between electrons and the parallel component of the wave electric field, heated electrons tend to focus to the midplane and their excursion amplitudes also become filamented in the steady state.

FILAMENTATION INSTABILITY IN MAGNETO PLASMAS

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ABSTRACT

It is shown that the filamentation of O mode pumps propagating at an arbitrary angle with respect to the magnetic field has to be magnetic field-aligned, but not for x mode pumps. A general dispersion relation is derived including the effects of magnetic field and collisions, and the nonlinear effects of ponderomotive force, thermal focusing force and the beating currents. Threshold field and growth rate are obtained and compared to the results of unmagnetized and collisionless case. Applications of these results to ionospheric modifications are discussed.

Excitation of Upper-Hybrid Waves by a Thermal Parametric Instability

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A purely growing instability characterized by a four-wave interaction has been analysed in a uniform, magnetized plasma. Up-shifted and down-shifted upper-hybrid waves and a non-oscillatory mode can be excited by a pump wave of ordinary rather than extraordinary polarization in the case of ionospheric heating. The differential Ohmic heating force dominates over the pondermotive force as the wave-wave coupling mechanism. The beating current at zero frequency produces a significant stabilizing effect on the excitation of short-scale modes by counterbalancing the destabilizing effect of the differential Ohmic heating. The effect of ionospheric inhomogeneity is estimated, showing a tendency to raise the thresholds of the instability. When applied to ionospheric heating experiments, the present theory can explain the excitation of field-aligned plasma lines and ionospheric irregularities with a continuous spectrum ranging from metre-scale to hundreds of metre-scale. Further, the proposed mechanism may become a competitive process to the parametric decay instability and be responsible for the overshoot phenomena of the plasma line enhancement at Arecibo.

Oscillating Two-Stream Instability of a Ducted Whistler Pump

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A magnetically field-aligned zero-frequency mode excited together with two lower hybrid sidebands by a ducted whistler pump is investigated. The thermal focusing force is found to be the dominant nonlinear effect on the excitation of large-scale instabilities; while the nonoscillatory beating current overrides the thermal focusing force in the short wavelength instabilities. Applications of these studies to space and laboratory plasmas arediscussed.

Analysis of the Electron Cyclotron Maser Instability

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ABSTRACT

A single nonlinear equation which describes the temporal evolution of the field amplitude of the electron cyclotron maser instability is derived self-consistently. The results deduced from this nonlinear equation are found to agree well with those of particle simulation.

Relativistic Adiabatic Invariants of Electron Motion Under ECRH

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ABSTRACT

Three adiabatic invariants of the electron motion under electron cyclotron resonance heating have been derived. The relativistic effect has been included in the analysis. It is also shown that the relativistic effect tends to focus the bouncing motion electrons to the midplane.

Earth's magnetic field perturbations as the possible environmental impact of the conceptualized solar power satellite (SPS)

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It is predicted that earth's magnetic field can be significantly perturbed locally by the microwave beam transmitted from the conceptualized solar power satellite (SPS) at a frequency of 2.45 GHz with incident power density of 230 W/m^2 at the center of the beam. The simultaneous excitation of earth's magnetic field fluctuations and ionospheric density irregularitieswith a comparable percentage is caused by the thermal filamentation instability of microwaves with scale lengths greater than a few kilometers. Large earth's magnetic field perturbations with magnitudes (> a few tens of γ's)comparable to those in magnetospheric (sub-)storms can be, therefore, expected. Particle precipitation and airglow enhancement are the possible, concomitant ionospheric effects associated with the microwave-induced geomagnetic field fluctuations. Our present work adds earth's magnetic field perturbations as an additional effect to those such as ionospheric density irregularities, plasma heating, etc. that should be assessed as the possible environmental impacts of the conceptualized solar power satellite program.

A Theoretical Model of Artificial Spread F Echoes

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ABSTRACT

Four invariants of the ray trajectory are found for a ray propagating in a horizontally stratified ionosphere under the density perturbation of HF wave-induced field-aligned irregularities. The reflection height of the ray can then be determined with the aid of those invariants. The results show that the reflection height of the ray varies drastically (namely, strong spread F echoes) in the presence of irregularities that polarize in the magnetic meridian plane. By contrast, the reflection height is not affected (namely, no spread F echoes) by those irregularities that polarize in the direction perpendicular to the meridian plane. Spread F is quite insensitive to the magnetic dip angle θ_0 in the region from 20° to 70°. The dependence of spread F on the scale length of the irregularity has also been examined for the case $\theta_0 = 50°$. It is found that spread F is not caused by irregularity with scale length less than about 100 meters.

Simultaneous Excitation of Large Scale Geomagnetic Field Fluctuations and Plasma Density Irregularities by Powerful Radio waves

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We elaborate upon the physical mechanism of thermal filamentation instability of radio waves whose frequencies can be as low as in the VLF band and as high as in the SHF band. This instability can excite large-scale magnetic and plasma density flucuations simultaneously in the ionosphere and magnetosphere. We comment on relevant experiments in terms of this instability and other mechanisms.

Turbulence in Unmagnetized Vlasov Plasmas

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Abstract

The classical technique of transformation and characteristics is employed to analyze the problem of strong turbulence in unmagnetized plasmas. The effect of resonance broadening and perturbation expansion are treated simultaneously without time secularities. The renormalization procedure in the sense of Dupree and Tetreault [1] is used in the transformed Vlasov equation to analyze the turbulence and to derive explicitly a diffusion equation. Analyses are extended to inhomogeneous plasmas and the relationship between the transformation and ponderomotive force is obtained.

Interaction of Relativistic Electron Beam with Large Amplitude Electromagnetic Wave in a Uniform Magnetic Field

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Abstract

Resonant interaction of an electron beam with a relativistically strong electromagnetic wave of right hand circular polarization propagating collinearly along a dc magnetic field $\vec{B}_o$ has been studied analytically. The analysis has taken the full nonlinearity of the relativistic effect into account. The result of the relativistic effect on the resonant interaction is to cause the wave intensity to oscillate at a frequency near $(\Omega_o/2\omega)^{1/2}\omega_p/\gamma_o$. It is found that there is an upper bound on the transverse velocity of the electron achievable through the interaction.

END

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